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TEMPERATURE MEASUREMENTS OF ROCKET FLAMES

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CONTENTS

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ABSTRACT

A field-type instrument for indirectly measuring rocket flame temperature by measuring its spectral emissivity and emission in the ultraviolet spectrum is described. Emission is measured by focusing an image of a selected point of the flame upon the entrance slit of a monochromator and recording the output of a photo multiplier placed at the monochromator exit slit. Emissivity is taken to be equal to the absorptivity, measured through the flame at the same selected point. These quantities are substituted into Wien's radiation law and temperature is calculated. Incorporated in the instrument are two chopper wheels which interrupt the light beam, allow essentially simultaneous recording of both quantities, and permit the use of ac amplifiers. The data is presented upon a cathode-ray tube and recorded upon 35-mm film. The optical portion of the instrument is mounted on a heavy iron stand to withstand the vibration produced by the motor and is transportable along the axis of the flame. Data is recorded as a function of distance from the motor throat.

Difficulty with unwanted noise signal was encountered and minimized while using the instrument on an oxygen-alcohol reaction motor. Further reductions of noise effects were obtained by averaging data over a time interval of a tenth of a second, which resulted in a temperature determination for every inch of travel from the throat. Preliminary temperature values of approximately 2400° K to 2600° K were measured.

The possibility of further reduction of noise signal is indicated, and plans to modify the existing instrument are in process. It is also planned to provide electronically averaged data recorded on ink recorders in addition to the unaveraged data recorded on film.

PROBLEM STATUS

This is a second report on rocket flame temperature measurements; work is continuing.

AUTHORIZATION

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TEMPERATURE MEASUREMENTS OF ROCKET FLAMES

INTRODUCTION

The general problem of missile guidance has brought up some interesting problems of electromagnetic propagation through high-velocity high-temperature flames. At least one classification of guided missiles, of necessity, receives the greater portion of its guidance information through the exhaust trail. The motive force in all contemplated missiles is one of various forms of reactors which expells high-velocity gas from the missile and thereby imparts a forward velocity. The possible forms of the reaction motors are numerous forms of heat engines, but invariably the high-velocity gas is produced by burning liquid or solid fuels at high temperature. It is conceivable that the ensuing exhaust stream may contain a large number of ions, thus forming an ionized medium, trailing out behind the missile for an appreciable distance. The ionized medium, if of sufficient volume and charge density, could represent a change of dielectric constant of the medium and could cause an appreciable loss in electromagnetic energy reaching the missile.

The Naval Research Laboratory has investigated[1,2,3,4,5] the loss of energy due to the exhaust flame at certain frequencies and in connection with certain reaction motors using specified fuels. The time and manpower required for the investigation to date has assumed large proportions. With the advent of new and highly complicated fuels, the task of individually checking each fuel at a specific frequency for each intended application greatly increases the manpower requirements. Thus, it is extremely desirable to find an acceptable general theory accounting for the loss of energy as electromagnetic waves pass through the gases of exhaust flames. In view of the evidence of the above investigation, it is assumed that electronic absorption is the most probable cause of energy loss. Saha, sometime ago, developed a theory accounting for electron production in a high-temperature gas. This theory has been extended to the case of burning gases, but there remains the task of experimentally justifying some of the assumptions and verifying the calculated results.

An important parameter entering the energy absorption theory is the temperature of the gas. Theoretical calculations of the temperature bases on certain unsubstantiated assumptions have been made, but there has been very little progress toward an actual measurement of the temperature. A few of the difficulties inherent in such a measurement are: (a) lack of

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[1] F. M. Gager, "Propagation of Electromagnetic Waves through Propellant Gases," NRL Report R-3197 (Confidential), November 1947

[2] F. M. Gager, E. N. Zettle, H. M. Bryant, F. E. Boyd, "S-Band Propagation with Acid-Aniline Flame Barrier," NRL Report R-3209 (Confidential), December 1947

[3] F. M. Gager, H. H. Grimm, R. C. Peck, G. D. Morehouse, "Incidental Flame Modulation of S-Band Continuous Wave Radiation," NRL Report R-3261 (Confidential), March 1948

[4] H. M. Bryant, D. L. Fye, "Transparency of an Acid-Aniline Flame to S-Band Radiation," NRL Report 3690 (Confidential), June 1950

[5] F. M. Gager, G. C. Schleter, "Electromagnetic Probes for Supersonic Flames," NRL Report 3505 (Confidential), June 1949

a single definition of temperature as applied to this case, (b) the high temperature involved, (c) the necessity of making the measurement without disturbing the high-velocity flame, (d) the necessity for remote observation because of the everpresent danger accompanying the operation of reaction motors, and (e) the high-intensity sound fields in the vicinity of the flame which impose severe requirements on optical and electronic systems operating close to the flame. With the above difficulties in mind the author embarked on a program of developing a suitable temperature-measuring instrument and measuring the temperature of the flames used in the more general investigation of the over-all problem.

THEORY

The instrument described in this report is patterned, in theory, after an indirect method for determining a flame's temperature by measurement of its emission and emissivity in a portion of the ultraviolet spectrum. The method was contributed by Curcio, Stewart, and Petty[6] of the Optics Division, Naval Research Laboratory, and the instrument was built after much consultation with them. For completeness, the important points of the theory will be repeated here.

The burning of hydrocarbons in oxygen gives rise to a strong neutral OH-radical band at about 3060°A which is composed of many narrow lines only resolvable by high-resolution-spectroscopic techniques. Dicke and Crosswhite[7] have shown these rotation lines to be in thermal equilibrium and this fact has been further verified by Wolfhard and Parker[8] in a line-reversal technique for measurement of flame temperature. This means that the emission of a flame, R, at any wave length in this OH band can be expressed as the product of the spectral emission of a black body, J, at the temperature of flame and the emissivity, E, of the flame at this wave length;

$$R = EJ. \tag{1}$$

It is assumed that in the case of transparent flames the absorptive power, A, of the flame for light traversing along a given path is equal to the spectral emissivity of the flame viewed along the same path;

$$A = E. \tag{2}$$

The absorptive power along a given path is the ratio of power absorbed to the incident power; thus

$$A = \frac{I_0 - I}{I_0} = E \tag{3}$$

where I_0 is the spectral power of the incident beam and I is the spectral power leaving the flame. Combining Equations (1), (2), and (3) gives

$$J = \frac{R}{E} = \frac{R\,I_0}{I_0 - I}\ . \tag{4}$$

[6] J. A. Curcio, H. S. Stewart, C. C. Petty, "A Method for the Determination of Flame Temperature from Emission in the Ultra-Violet OH Band," J.O.S.A. 41, 173–179, 1951

[7] G. H. Dicke and H. M. Crosswhite, "The Ultra-Violet Band of OH," Johns Hopkins University Applied Physics Lab., Bumble-Bee Report 87 (Unclassified), November 1948

[8] H. G. Wolfhard, W. G. Parker, "Combustion Processes in Flames, Part VI, A New Technique for the Spectroscopic Examination of Flames at Normal Pressures," Royal Aircraft Establishment Report No. Chem 457 (Unclassified), March 1949

Since the spectral intensity of a black body is a well-known function of temperature,

$$J = \frac{C_1}{\lambda^5} e^{-\frac{C_2}{\lambda T}} \qquad (5)$$

where λ is the particular wavelength used, C_1 and C_2 are radiation constants, and T is the temperature in degrees Kelvin, the temperature can be calculated in terms of R, I_0, and I.

The instrument described below is not capable of measuring spectral intensities at a single wavelength. It integrates over a small finite wavelength interval such that Equation (4) must be altered to read average values; thus

$$\overline{J} = \overline{\left[\frac{R}{E}\right]} \qquad (4a)$$

or

$$\overline{J} = \frac{\overline{R}}{\overline{E}} \qquad (4b)$$

This theory does not determine or use any existing temperature gradient along the observation path through the flame; therefore, any calculated temperature is an average temperature lying between the lowest and highest temperature along the optical path. Qualitative evidence as to the nature and magnitude of the temperature gradient based upon calculated relative radiation density and an assumed temperature at the center of the flame has been presented by Wyman.[9] While no attempt is made to determine the manner in which the measurements by the subject method are weighted, it is thought that they lie nearer the highest temperature. This thought is based upon the fact that the low temperatures at the edge of the flame are below the sensitivity threshold of practical instruments.

DESCRIPTION OF THE INSTRUMENT

The basic temperature-measuring instrument consists of a hydrogen lamp, an optical system, a Perkin Elmer monochromator, a 1P28 photomultiplier, and a recording system (Figure 1). An instrument suitable for field use which embodies these features is shown mounted on a sturdy iron stand made of 4-inch channel in Figure 2. The protective covers are removed to show the hydrogen-lamp power-supply filter, hydrogen arc lamp, chopper C_1, lens ℓ_1, lens ℓ_2, chopper C_2, monochromator, photomultiplier (inside monochromator), and the photomultiplier power supply and cathode follower mounted underneath the monochromator. This assembly is placed at right angles to the axis of the flame with the flame crossing the optical axis of the instrument at point A (Figure 1) midway between ℓ_1 and ℓ_2. Figure 3 shows the opposite side of the same assembly with protective aluminum shields in place. The remaining units — the main power supply and the recording and viewing oscilloscope (Figure 4) — are mounted in a standard relay rack and are placed at any convenient distance, up to 200 feet from the flame.

An additional unit, a ribbon-filament spectroscopic lamp, is necessary for calibration. This lamp is placed on the optical axis (Figure 1, point A) halfway between ℓ_1 and ℓ_2. The filament coincides with the position of the hydrogen lamp image in the flame. Some 40 to 75 amperes of direct current at less than 3 volts is supplied the filament of this lamp by a three-phase Mallory Rectostarter. The trace on the recording oscilloscope tube (Figure 4) is recorded by a DuMont 314 oscilloscope camera.

[9] F. E. Wyman, "Relative Radiation Density and Temperature Distribution of Rocket Flames," NRL Report 3823 (Restricted), 10 July 1951

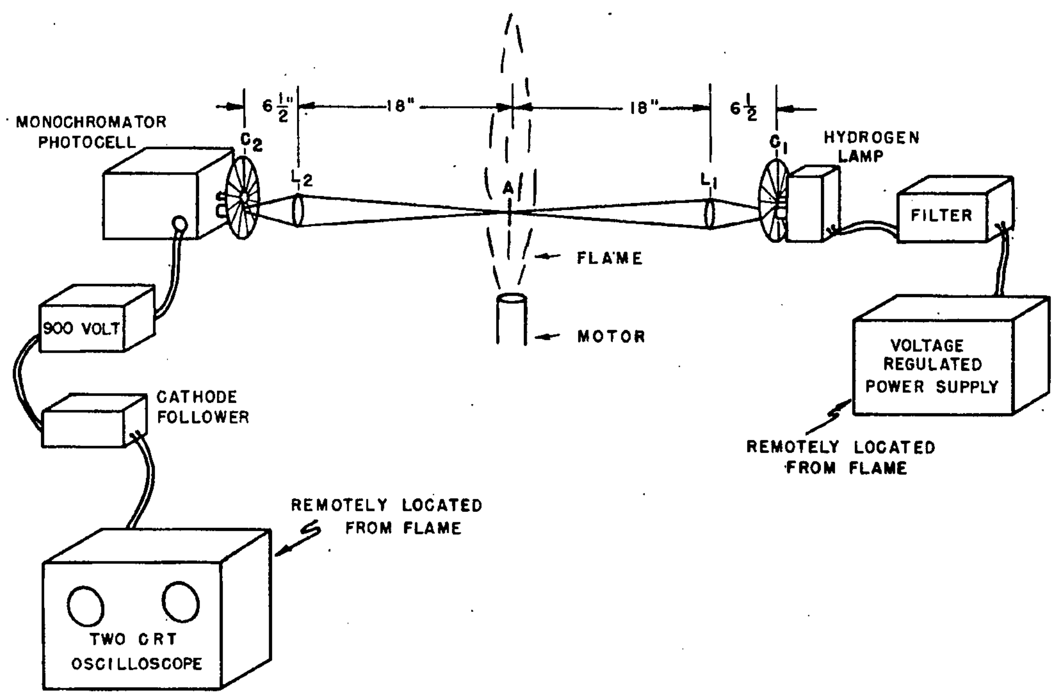

Figure 1 - Block diagram of temperature-measuring instrument

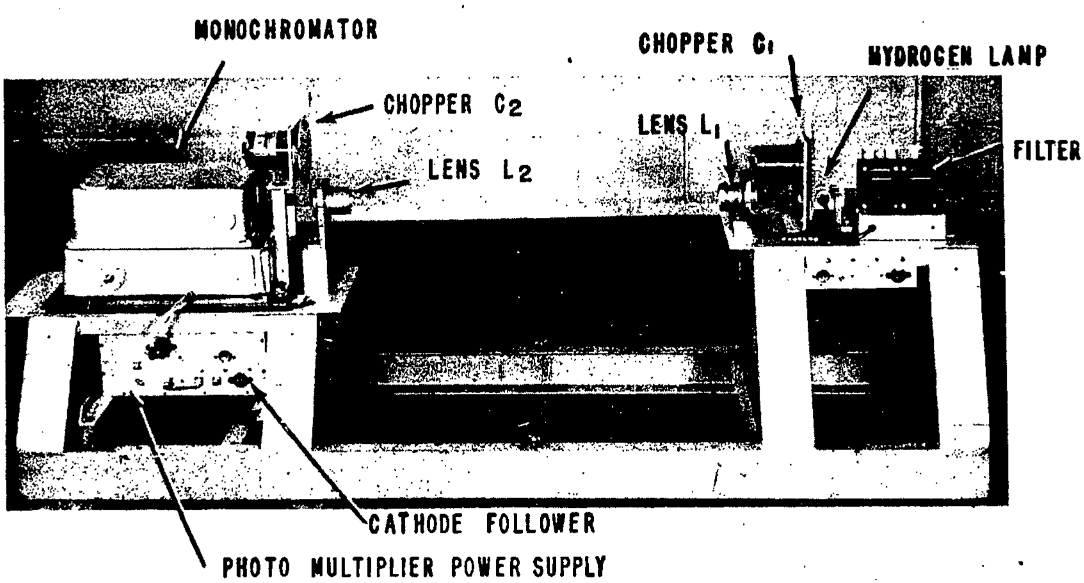

Figure 2 - Temperature-measuring instrument with protective shields removed, front view

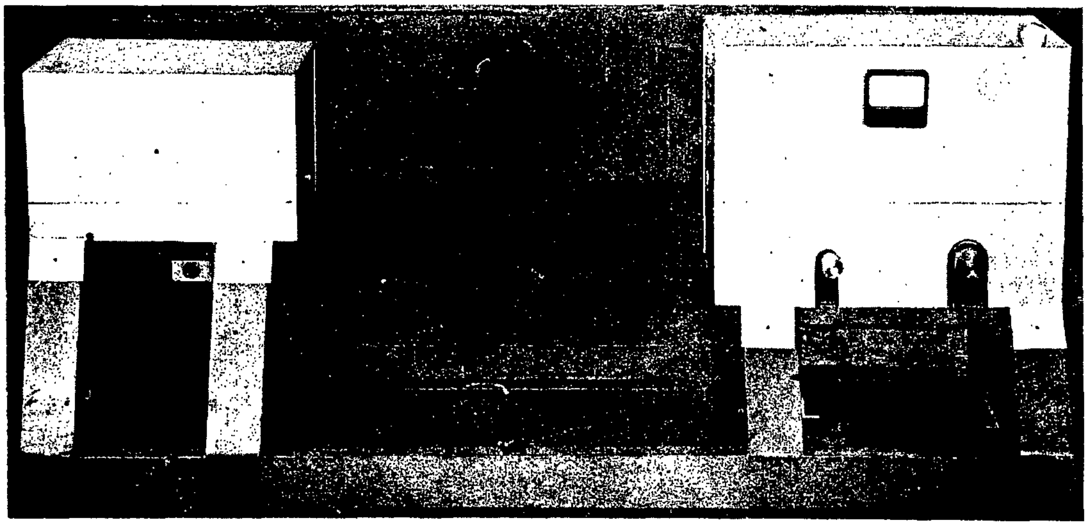

Figure 3 - Temperature-measuring instrument with protective shields in place, rear view

The general characteristics of the various components are given in Table 1.

OPERATION OF INSTRUMENT

The theory previously set forth involves a measurement of the quantities I_0, I, and R. The temperature-measuring instrument records on 35-mm film a trace from which deflections H_0, H_f, and F can be obtained. The letter quantities are related as follows:

$$H_0 \; \alpha \; I_0$$
$$H_f \; \alpha \; I$$
$$F \; \alpha \; R.$$

Three types of idealized film traces are shown in Figure 5. Trace a shows the recording of the instrument with the hydrogen lamp excitation but without flame. The square wave pattern shown is produced by the action of choppers C_1 and C_2 upon the beam of light passing from the hydrogen lamp to the monochromator. The deflection H_0 is proportional to the spectral intensity of the hydrogen lamp.

Trace b is made with the hydrogen lamp emission passing through the flame. The total deflection D, recorded at a time when both choppers are open, is proportional to the spectral emission of the flame plus the

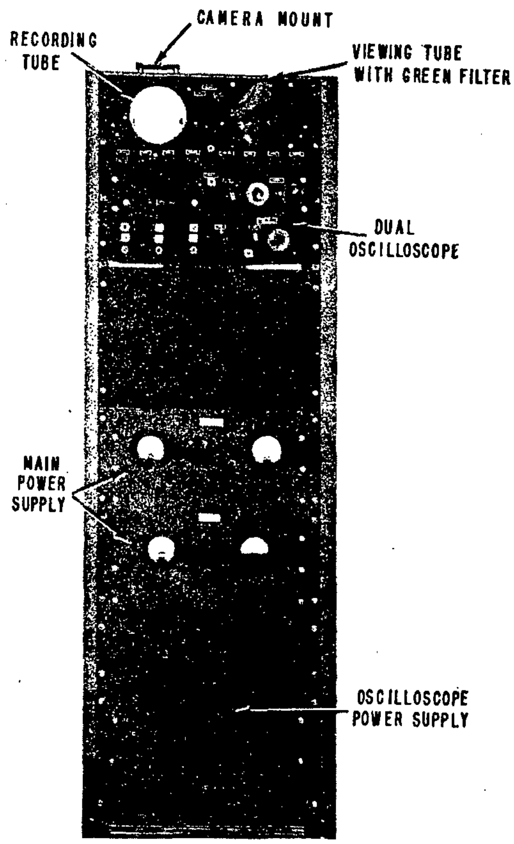

Figure 4 - Viewing and recording oscilloscopes with power supplies

TABLE 1

Characteristics of Temperature-Measuring Instrument Components

Component	Characteristics
Hydrogen lamp power supply	Variable current from 100 to 300 ma, constant current supply.
Filter	Inductance-capacitance filter in close proximity to lamp.
Hydrogen arc lamp	Beckman hydrogen lamp.
Chopper C_1	36-slit interrupter wheel driven by a variable-speed motor. Interrupting frequency is 200 to 2200 cycles.
Lens ℓ_1 and ℓ_2	Simple quartz lens, focus 5-1/4 inches, f/3.5.
Chopper C_2	3-slit interrupter wheel driven by 1800-rpm synchronous motor, interrupting frequency is 90 cycles.
Monochromator	Perkin– Elmer model 83, effective aperture f/4.5 crystal quartz prism.
Photomultiplier tube	1P28
Photomultiplier power supply	900 volts made up of Minimax B batteries
Cathode follower	
Oscilloscope	Two cathode-ray-tube oscilloscope copied after TS-239/UP, band width is approx. 4 Mc. 1 - 5CP11 tube 1 - 5CP1 tube
Camera	DuMont 314 oscilloscope recording camera f/2, run at speeds between 20 and 60 inches of film per second.
Film	Eastman Linograph Ortho

spectral intensity of the hydrogen lamp that emerges from the flame, $F + H_f$. Deflection F is recorded at a time during which C_1 is interrupting the beam from the hydrogen lamp and, therefore, F is proportional to the spectral intensity of the flame.

The third trace, c, is made for calibration purposes. The light producing the deflection D_W comes from the calibrated tungsten lamp placed at the center of the flame position

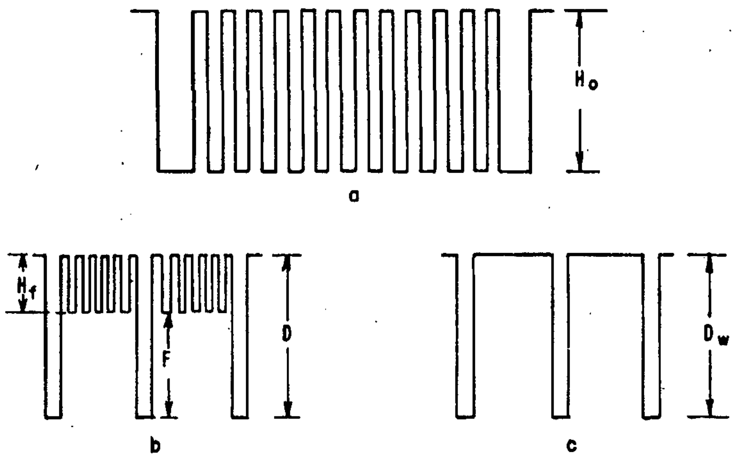

Figure 5 - Idealized recording film traces

(Figure 1, point A). It is therefore proportional to the spectral intensity of the tungsten. The lamp is calibrated in terms of absolute temperature and its black-body spectral intensity is well known.

In the case of traces, a, b, and c, the base line is established when chopper C_2 is interrupting the light beam entering the monochromator. The choppers perform two functions — first they permit the use of ac amplifiers in the electronic part of the recording system, and secondly they allow two quantities to be measured from one trace.

Of the quantities H_0, H_f, and F, H_0 is assumed to remain constant with time. This is assured by constant monitoring of the lamp current and frequent comparison recordings of the deflection H_0. Theory requires H_f and F to be measured instantaneously. In this application of the theory the requirement is approximated to a reasonable degree. The square wave pattern produced by the choppers allows quantities H_f and F to be measured during a time interval not greater than the rise time which is a function of the rotational velocity of the chopper wheels and the bandwidth of the electronic system. This time interval can be made as short as is consistent with the limitations imposed by the total bandwidth requirements. However, if shorter rise time is required, the correspondingly greater necessary bandwidth allows an increase in noise signal amplitude which, in turn, introduces greater uncertainty in the determination of the deflections F, D, and H_0. In the present instrument the rise time and fall time of the square wave is approximately 80 microseconds. The hydrogen lamp spectral intensity can be assumed to be constant for a much greater time. If it can be assumed that the flame is changing slowly over the referenced period of time, the measurement of H_0, D, and F by this method can be considered to be simultaneous with small error.

The deflections H_0, D, and F are taken directly from the film recording and H_f is calculated thus:

$$H_f = D - F.$$

Properties of the system can be set down as follows:.

h — spectral intensity of hydrogen lamp,
t — spectral transmission of the monochromator,

s — spectral sensitivity of the recording system,
E — spectral emissivity of the flame at temperature T,
J — spectral intensity of a black body at the temperature of the flame,
G — an optical-geometric factor involving lens ℓ_1 and ℓ_2,
G′ — an optical-geometric factor involving lens ℓ_2 only.

H_0 depends upon h and the system; H_f depends upon h, the flame, and the system; and F depends upon the flame and the system.

$$H_0 = G \int_{\lambda_1}^{\lambda_2} hts \, d\lambda \tag{6}$$

$$H_f = G \int_{\lambda_1}^{\lambda_2} h(1-E)ts \, d\lambda \tag{7}$$

$$F = G' \int_{\lambda_1}^{\lambda_2} EJts \, d\lambda \tag{8}$$

Since any physical measuring device is incapable of measuring a discrete frequency, and of necessity must measure an average quantity integrated over a finite frequency interval, the following definition of average values will be used.

$$\overline{E} \equiv \frac{\int_{\lambda_1}^{\lambda_2} Ehts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} hts \, d\lambda} \tag{9}$$

$$\overline{J} \equiv \frac{\int_{\lambda_1}^{\lambda_2} JEts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} Ets \, d\lambda} \tag{10}$$

$$\overline{h} \equiv \frac{\int_{\lambda_1}^{\lambda_2} hEts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} Ets \, d\lambda} \tag{11}$$

$$\overline{R} \equiv \frac{\int_{\lambda_1}^{\lambda_2} Rts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} tsd\lambda} \tag{12}$$

Substituting Equation (8) into Equation (10) gives

$$\overline{J} = \frac{F}{G' \int_{\lambda_1}^{\lambda_2} Etsd\lambda} \; . \tag{13}$$

Substituting Equation (11) into Equation (13) gives

$$\overline{J} = \frac{F \quad \overline{h}}{G' \int_{\lambda_1}^{\lambda_2} hEtsd\lambda} \, . \tag{14}$$

The substitution of Equation (9) into Equation (14) results in

$$\bar{J} = \frac{F}{G'\,\bar{E}} \, \frac{\bar{h}}{\int_{\lambda_1}^{\lambda_2} hts\,d\lambda}. \tag{15}$$

Substituting Equation (6) into Equation (15) gives

$$\bar{J} = \frac{G}{G'} \, \frac{\bar{h}}{H_0} \, \frac{F}{\bar{E}}. \tag{16}$$

Equation (6) can be written

$$H_0 = G \int_{\lambda_1}^{\lambda_2} tsd\lambda \; \frac{\int_{\lambda_1}^{\lambda_2} hts\, d\lambda}{\int_{\lambda_1}^{\lambda_2} ts\, d\lambda} = k\,G\,\bar{h}' \tag{17}$$

where $k = \int_{\lambda_1}^{\lambda_2} tsd\lambda$ is recognized as a constant of the system.

$\bar{h}'$ is a legitimate average value of h but in general $\bar{h} \neq \bar{h}'$. $\bar{h} = h(\lambda')$ and $\bar{h}' = h(\lambda'')$ where $\lambda_1<\lambda^1<\lambda_2$ and $\lambda_1<\lambda''<\lambda_2$ but $\lambda' \neq \lambda''$. If $\Delta\lambda = \lambda_2 - \lambda_1$ is made sufficiently small, $\bar{h}$ can be taken equal to $\bar{h}'$ with negligible error. This allows Equation (17) to be written

$$H_0 = k\,G\,\bar{h} \tag{17a}$$

and upon substitution Equation (16) becomes

$$\bar{J} = \frac{G}{G'} \, \frac{\bar{h}}{kG\bar{h}} \, \frac{F}{\bar{E}} \tag{18}$$

or, rearranging,

$$F = k\,G'\,\bar{E}\,\bar{J} = K\,\bar{E}\,\bar{J} \tag{18a}$$

where $K = k \cdot G'$.

Using Equations (6), (7), and (9) emissivity can be written

$$\bar{E} \equiv \frac{\int_{\lambda_1}^{\lambda_2} hEts\, d\lambda}{\int_{\lambda_1}^{\lambda_2} Ets\, d\lambda} = \frac{H_0 - H_f}{H_0}.$$

Thus Equation (18a) can be written

$$\bar{J} = \frac{1}{kG'} \, \frac{H_0}{H_0 - H_f} \; F. \tag{18b}$$

Or solving for T, the flame temperature, with the aid of Equation (5) and the assumption that $J(T) = \overline{J}$,

$$T = \frac{C_2}{\lambda} \frac{1}{\ln\left\{\frac{C_1}{\lambda^5} \frac{kG'}{F} \frac{(H_0 - H_f)}{H_0}\right\}} .$$

Equation (18a) can be brought into the form of Equation (4b) by writing Equation (8) as

$$F = G' \int_{\lambda_1}^{\lambda_2} Rts \, d\lambda \quad . \tag{8a}$$

Multiplying through by $\int_{\lambda_1}^{\lambda_2} ts \, d\lambda$,

$$F = G' \int_{\lambda_1}^{\lambda_2} ts \, d\lambda \, \frac{\int_{\lambda_1}^{\lambda_2} Rts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} ts \, d\lambda} , \tag{19}$$

which upon substituting Equation (12) gives

$$F = G' k \overline{R} = K \overline{R} . \tag{20}$$

Combining Equations (18a) and (20) gives

$$\overline{R} = \overline{E} \, \overline{J} \tag{21}$$

which is indeed Equation (4b); therefore the recorded deflections have been associated with the theory.

Calibration consists of determining the constant $kG' = K$. A tungsten lamp of known characteristics is placed at point A (Figure 1). A recording similar to the one shown in Figure 5c is made and the deflection D_W noted.

$$D_W = G' \int_{\lambda_1}^{\lambda_2} J_W E_W ts \, d\lambda = G' \int_{\lambda_1}^{\lambda_2} R_W \, ts \, d\lambda \tag{22}$$

where J_W — spectral intensity of a black body at temperature of tungsten filament,
E_W — spectral emissivity of tungsten at temperature of filament.

$$\overline{R}_W \equiv \frac{\int_{\lambda_1}^{\lambda_2} R_W \, ts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} ts \, d\lambda} . \tag{23}$$

Multiplying Equation (22) by $\int_{\lambda_1}^{\lambda_2} ts \, d\lambda$ gives

$$D_W \equiv G' \int_{\lambda_1}^{\lambda_2} ts \, d\lambda \frac{\int_{\lambda_1}^{\lambda_2} R_W ts \, d\lambda}{\int_{\lambda_1}^{\lambda_2} ts \, d\lambda} , \tag{24}$$

and substituting Equation (23) results in

$$D_W = k\,G'\,\bar{\bar{R}}_W \ . \qquad (25)$$

For a given temperature of the tungsten filament R_W will be known and D_W will be recorded; thus $G'k$ can be calculated.

TEMPERATURE DETERMINATION OF ROCKET FLAMES

Preliminary to field use of the subject temperature-measuring equipment, a laboratory comparison of the temperature of an oxygen-acetylene torch, measured by this method and the sodium-line-reversal method, was conducted. While the comparison was incomplete and conducted in haste in order to meet the departure time for a field trip, the results indicated agreement between the two methods to within a reasonable degree. This agreement was not as close as the agreement indicated by Curcio, Stewart, and Petty,[10] but it should be noted that in the latter case the instrument was calibrated by the sodium-line-reversal method and subsequent comparison with sodium-line-reversal temperature should be expected to be favorable. In the comparison discussed here calibration was made by means of a tungsten lamp.

Actual field measurements of rocket flame temperatures using the above described equipment were taken during June of 1950 at the rocket-test cells of Reaction Motors Inc., Lake Denmark, New Jersey. The flame temperature of the Reaction Motors Inc. 1500-pound-thrust alcohol-oxygen motor was measured for the most part; but some measurements were made on the flame of the 400-pound-thrust acid-aniline motor manufactured by the same company.

The instrument was mounted upon a movable carriage with the longitudinal axis of the flame passing at right angles to the optical axis (Figure 1, point A). The carriage was capable of moving down the flame axis for a maximum distance of 20 feet, but the plume-shaped flame restricted the usable travel to about 7 feet. The carriage speed was approximately 4-1/4 inches per second; hence the instrument could traverse its usable distance in the time of a 30-to 45-second motor run. Figures 6 and 7 show the instrument and movable carriage in front of a 1500-pound-thrust motor. The power supplies and the recording parts of the instrument (Figure 4) were mounted in a semitrailer freight van positioned some 200 feet from the rocket motor.

During field use, any one temperature determination consisted of three parts. When the rocket motor had been completely fueled and pressurized, but before it was fired, a recording was made similar to trace a (Figure 5) using radiation from only the hydrogen lamp. From this recording, of which a typical example is trace a (Figure 8), the deflection H_0 can be obtained. Immediately thereafter the motor was fired and, after stable operation had been reached, the recording camera and movable carriage were set in operation. From the resulting portion of trace b (Figure 8) the deflection D and F can be obtained. When the fumes and vapor which occur at the end of a motor run had cleared away, the H_0 trace was retaken and an agreement between the before and after H_0 deflections gave assurance that the gain of the amplifier, optical adjustment, or other sensitivity factors of the instrument had remained constant during the short elapsed time. Immediately following the recording of these three traces, the standardized tungsten lamp was positioned in the path of the flame (Figure 1, point A) and calibration trace c (Figure 8) recorded, from which the deflection D_W was obtained. The above procedure was followed in every determination, or motor run, and thus verified short time stability and eliminated the need for long time stability of the instrument.

[10] Curcio, Stewart, and Petty, loc.cit.

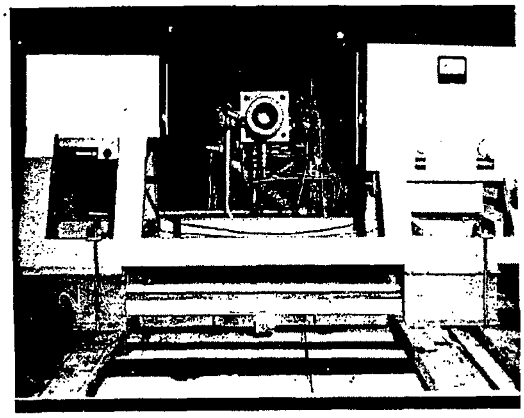

Figure 6.- Temperature-measuring equipment on movable carriage in front of rocket motor, rear view

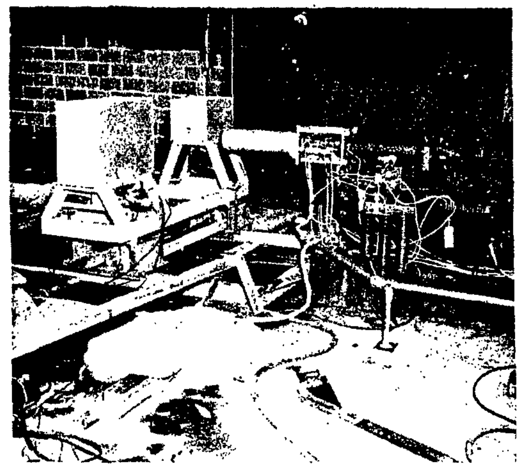

Figure 7 - Temperature-measuring equipment on movable carriage in front of rocket motor, front view

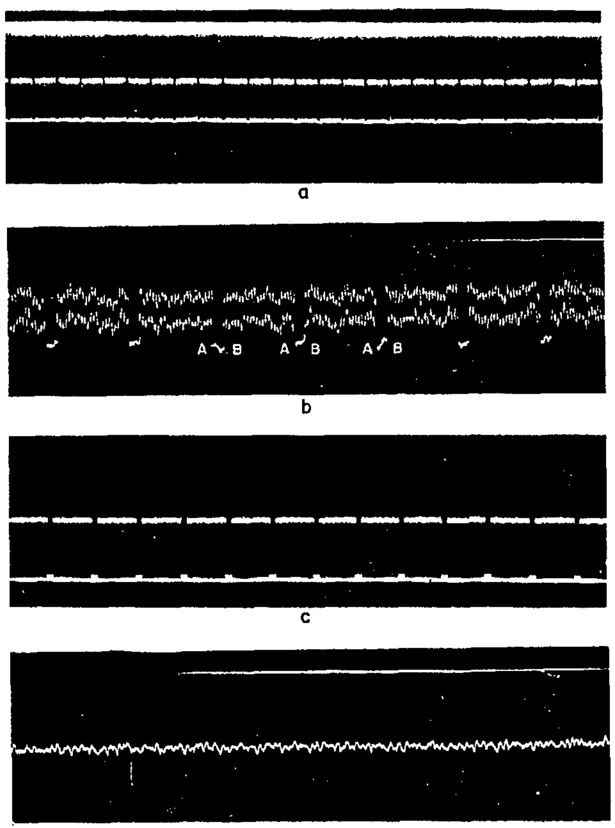

Figure 8 - Typical data recordings

It will be observed that there are appreciable differences in appearance between the idealized traces of Figure 5 and the typical traces of Figure 8. These differences, which tend to decrease the accuracy of measurement, can be attributed to the presence of noise signal. The broad and fuzzy nature of the top and bottom of the square waves is due to the presence of photomultiplier noise, which is regrettable but difficult to reduce. This noise is caused by the statistical nature of the electron flow within the tube and is proportional, in a complex manner, to the illumination falling on the tube. The 1P28 photomultiplier was operated with an anode current of approximately 15 microamperes which is above the region where artificial cooling would decrease the noise. In addition, there is a noise signal due to the instrument's being in a high-intensity-vibrational sound field. This noise signal shows itself on the base line in the absence of an optical signal (Figure 8, trace d) and is superimposed on the optical signal of all traces of type b (Figure 8).

For the convenience of relating a given portion of a trace to the corresponding position in the flame, distance code marks were superimposed on the film for every inch that the instrument traveled down the length of the flame.

DISCUSSION OF DATA

The photographic film was processed in the field to insure that sufficient data had been recorded. Upon return to the Laboratory, it became apparent that noise superimposed upon the useful data would mask the desired deflection to an appreciable extent. Since many more individual temperature measurements had been recorded than were needed, an averaging system was devised. Data was taken from the film near the points at which the trace returned to the base line such as A and B (Figure 8, trace b). Thus the time interval between a deflection and a known base point was kept very short and noise could not affect the reading to any great extent. Furthermore all the recordings thus taken, falling under a single inch marker, were averaged to give a more nearly correct and noise-free deflection. It is estimated that during the time covered by this average the instrument moved down the flame a distance of three times the diameter of the beam of light at its point of focus in the flame (Figure 1, point A). Under these conditions the spacial resolving power of the instrument has been lowered by as much as a factor of two, but this seems to be a reasonable price to pay for the reduction of error due to noise. By using this averaging system a temperature measurement is obtained every inch of the length of the flame and every 0.23 of a second.

Data was taken during 21 oxygen-alcohol and 5 acid-aniline motor runs. Three representative oxygen-alcohol runs have been analyzed and the results are presented in Figures 9, 10, and 11. One acid-aniline motor run has been analyzed, but the results are not presented because the spectral radiant energy eminating from the acid-aniline flame was of such low intensity as to be recorded only slightly higher than the noise signal. It is believed that the subsequently proposed refinements of the instrument will allow a significant measurement of this type flame to be made in the future.

A fair agreement will be observed between the separate oxygen-alcohol runs. In all cases the temperature directly in front of the motor throat is somewhat lower than the minimum appearing between mach nodes. The temperature rises to a maximum at the first mach node and then falls to a new minimum between the first and second node, with this pattern repeating itself down the axis of the flame. At approximately the sixth node the trend is toward lower temperature. Examination of a typical photograph of the flame (Figure 12) reveals that at the sixth node the flame structure is rapidly becoming indistinct.

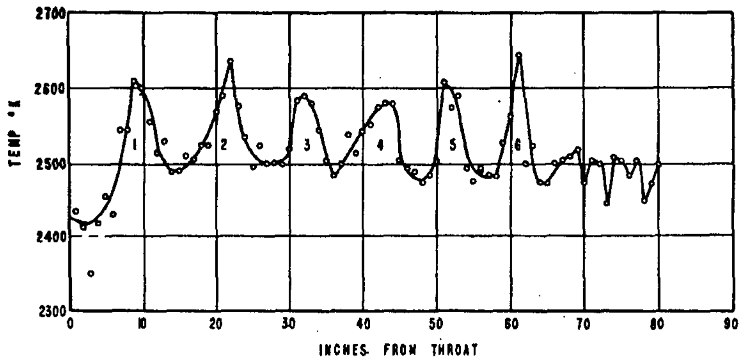

Figure 9 - Temperature vs. inches from motor throat - Run No. 11

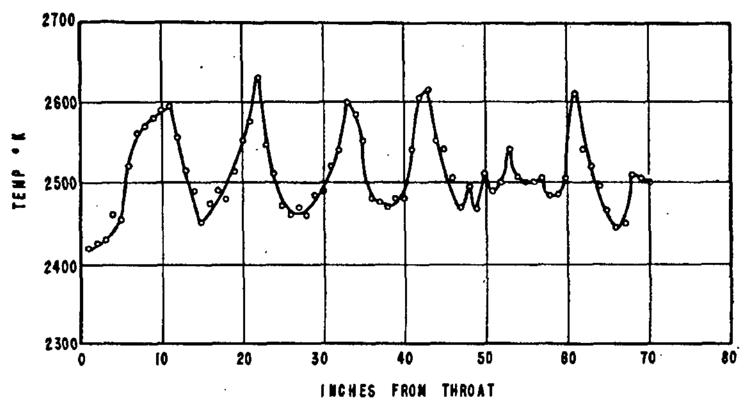

Figure 10 - Temperature vs. inches from motor throat - Run No. 21

The temperature pattern repeats itself from run to run, except for a difference in the indicated absolute value. For example, in the case of run No. 11 (Figure 9) and run No. 21 (Figure 10) the average minimum appears to be approximately 2475°K. Run No. 22 (Figure 11), except for some scattered points, indicates the average minimum as roughly 2550°K. The difference of 75° between these runs is not readily explained, but it is possible that it is caused by individual differences in the runs, or by differences in the character of the superimposed noise signal that has not been adequately averaged out. The operating data pertaining to each run is presented in Table 2.

Curcio, Stewart, and Petty[11] have shown that the emissivity of a laboratory-type bunsen flame varied with time. Figures 13, 14, and 15 present the variation of emissivity of a rocket motor flame versus distance from the motor throat. Although it is estimated that the averaging process has removed any time dependent variations, it will be observed that the emissivity varies through wide limit in a fairly disorderly manner. Close comparison with the corresponding temperature plot will show a tendency for emissivity to be high at the position of a mach node and low in the region of an antinode. Rapid, invisible variation of the flame along the longitudinal axis due to combustion-chamber complex-acoustic

[11] Curcio, Stewart, and Petty, loc.cit.

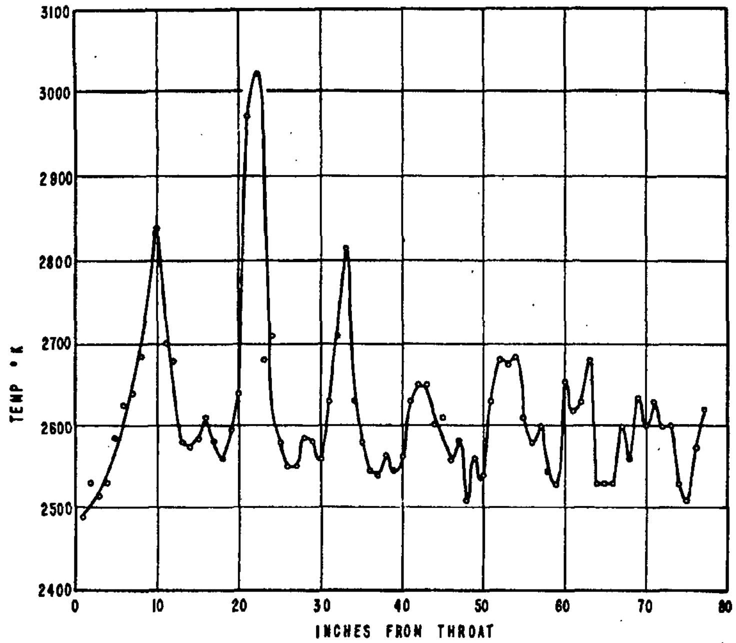

Figure 11 - Temperature vs. inches from motor throat - Run No. 22

Figure 12 - Flame from 1500-lb-thrust oxygen-alcohol motor

TABLE 2
Operating Data

Run No.	Inlet Pressure (psi)		Chamber Pressure (psi)	Fuel-to-Oxygen Ratio	Thrust (lb)
	Liquid Oxygen	Alcohol			
11	302	297	230	0.863	1634
21	300	300	235	0.856	1720
22	300	300	236	0.856	1695

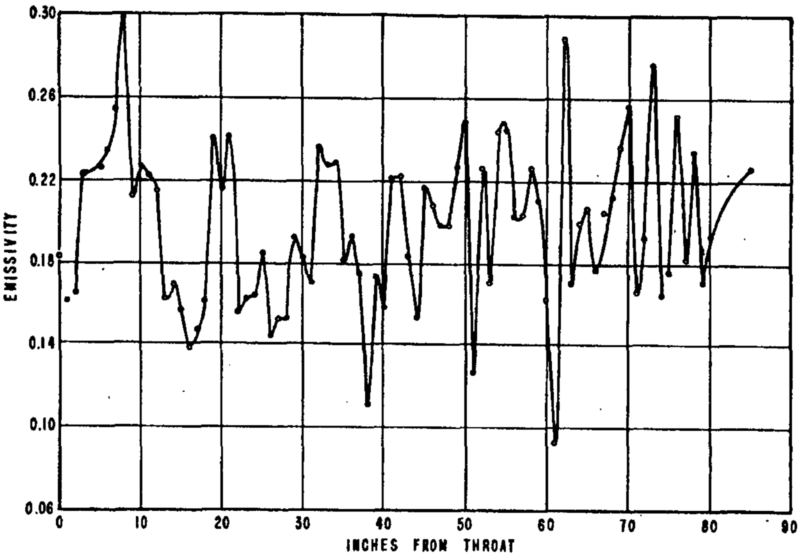

Figure 13 - Emissivity vs.distance from motor throat - Run No. 11

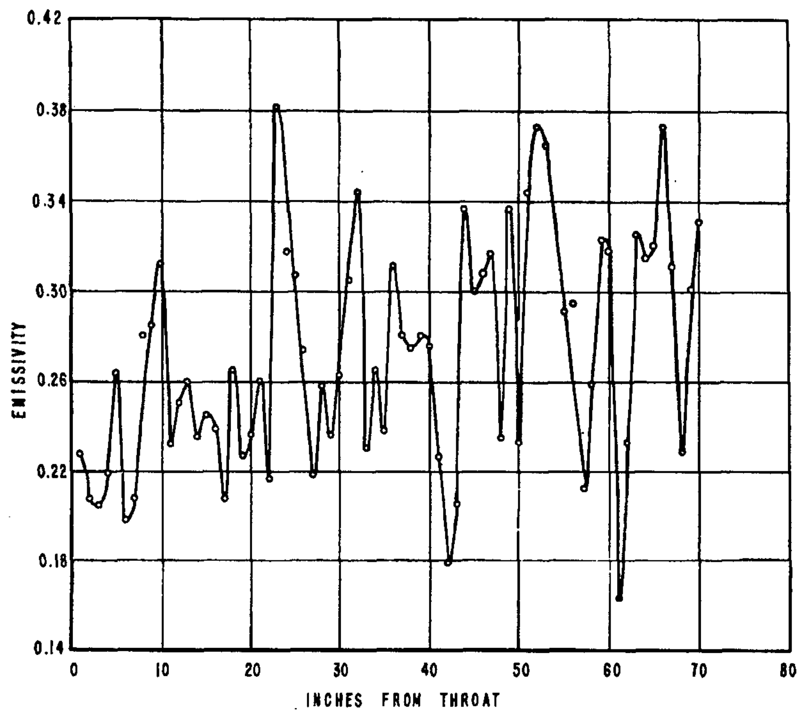

Figure 14 - Emissivity vs. distance from motor throat - Run No. 21

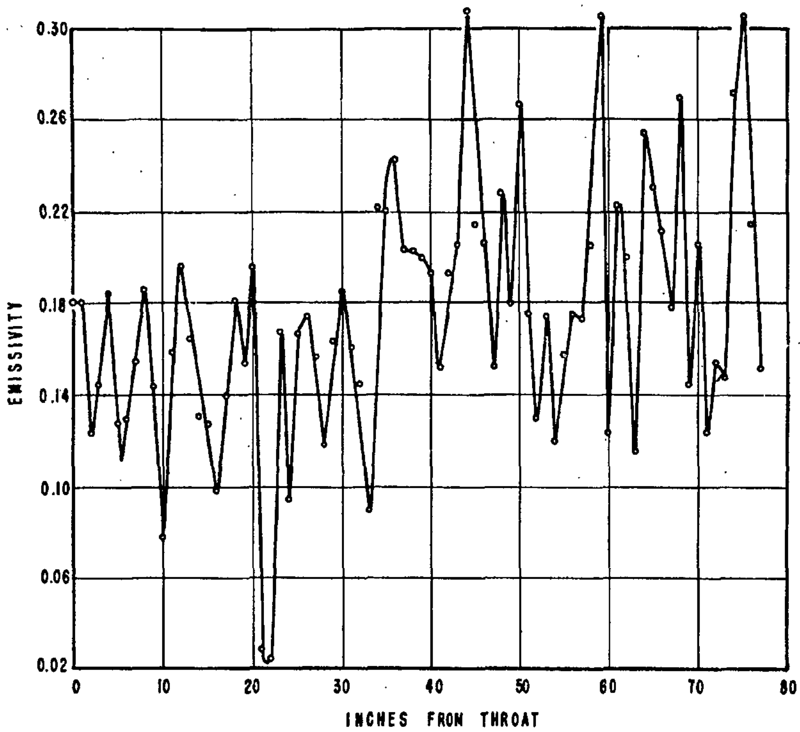

Figure 15 - Emissivity vs. distance from motor throat - Run No. 22

oscillation could account for some variation but is difficult to see how this phenomenon can explain all the indicated results.

PROPOSED IMPROVEMENTS AND FUTURE PLANS

The results presented in this report are considered by the author to be of an exploratory nature. Certain definite trends and approximate temperatures can be read, but it is believed that indicated improvements of equipment will result in more accurate and satisfactory data and measurements.

Field work with a rocket motor has shown that a large proportion of the superimposed noise signal can be removed, thus eliminating the need for the employed method of averaging. While operating the subject equipment near a rocket motor in high acoustic fields, it was determined that approximately two-thirds of the random noise signal was due to variations in photocell current brought about by vibration of the battery power. Since the variations were due to microphonic connections and leakage path changes, it is believed that an electronic high-voltage supply remotely located from the equipment will result in the elimination of much of this noise. This modification will result in more accurate measurements as well as increase the spacial resolution of the instrument to the inherent optical-geometric limit. In addition, it will decrease the time interval over which a measurement is made and allow an increase in the number of discrete temperature measurements per second. For certain types of flames and measurements this will be of extreme value.

In some cases an average temperature measurement is more desirable than a large number of separate instantaneous measurements. Proposed modification of the present instrument will include means for obtaining average temperature measurements as well as improved means for instantaneous measurements. To accomplish this, the output of the photomultiplier will be tapped, and a portion of the signal consisting of square waves of two widely separated frequencies will be diverted into a frequency-separating element. The resulting two outputs will carry square waves whose amplitudes are proportional to $F + H_f$ and H_f respectively. Any degree of integration could be provided and the integrated outputs recorded on recording voltmeters. The recorded information would be of a more readily usable nature suitable for easy and quick conversion to a temperature figure.

One further modification is planned. The hydrogen arc lamp supplying the light transmitted through the flame is to be replaced with a General Electric Spectroscopic Lamp. The only requirement for this lamp is that it supply sufficient spectral radiant energy at a wave length at which there is appreciable radiation in the flame, which meets the requirements of equilibrium. At present the equipment makes use of the ultraviolet molecular OH band. The substituted tungsten lamp has sufficient radiant energy in the ultraviolet range and in addition can be used with, for example, the sodium D line if sodium is introduced into the flame as an additive in the fuel. This line as well as others are known to be in thermal equilibrium.

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TEMPERATURE MEASUREMENTS OF ROCKET FLAMES

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FLAMES - TEMPERATURE	POWER PLANTS, ROCKET (4)
FLAMES, EXHAUST	COMBUSTION (5)

[redacted]